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To cite this article: D. Frómeta *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **651** 012071

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# Fracture toughness measurements to understand local ductility of advanced high strength steels

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**Abstract.** The determination of the material parameters that best predict the local ductility of high strength sheet materials has become the focus of active research. Even though several correlations have been proposed, they can sometimes be not accurate enough and discussion is still open on this topic. This paper investigates the suitability of different fracture toughness measurements for local ductility prediction in multiple advanced high strength steels (AHSS). Fracture toughness is characterized by means of essential work of fracture and Khan tear tests. The results show that the essential work of fracture,  $w_e$ , correlates well with different local formability (HER, critical bending angle from V-bending tests and local strain at fracture from uniaxial tensile tests) and crash resistance parameters (energy absorbed in axial impact tests). It confirms that fracture toughness, measured in the frame of fracture mechanics, is a relevant material property to rationalize cracking issues associated to the local ductility of AHSS. On the other hand, it is also shown that Khan tear tests, which are conventionally used to evaluate the fracture resistance of thin metal sheets, can overestimate crack propagation resistance and offer a poor prediction ability for local formability and crash performance.

## 1. Introduction

A wide variety of new high strength sheet materials have been developed in the last years for automotive lightweight applications. The limited ductility of these materials has posed new forming challenges that cannot be rationalized through conventional fracture characterization criteria. This fact has motivated the development of alternative characterization methodologies and improved formability mappings accounting for global and local formability. Global formability refers to the material resistance against necking instability and is well described by traditional tensile parameters (true uniform strain, elongation at fracture,  $n$ -value) and forming limit diagrams. Nevertheless, these tests provide little information regarding local formability issues (edge cracking, fractures occurring during bending on tight radius, crash folding behaviour). Thus, new experimental approaches are necessary to predict this kind of fractures associated to the local ductility of the material.

In this sense, recent research works have demonstrated that fracture toughness, measured within the frame of fracture mechanics, is a relevant material property to describe such cracking related problems in AHSS [1-5]. Many works have shown the suitability of fracture toughness to rationalize and classify the stretch flangeability of high strength steels [1-4]. More recently, the measurement of fracture toughness has been also used in [5] to understand the crash failure behaviour of different AHSS grades. Therefore, it is evident that there is a close relationship between the crack propagation resistance of high



strength metal sheets and its local ductility. Nevertheless, the measurement of fracture toughness according to elastic plastic fracture mechanics (EPFM) standards [6] is rather complex and involves exhaustive specimen preparation and test monitoring, which hamper its implementation as a routine testing in automotive industry. There exist alternative simpler methods to characterize the fracture toughness of thin metal sheets, such as the essential work of fracture (EWF) methodology [7].

The EWF methodology is easier than standard methods since it permits to obtain the material crack initiation and propagation resistance without measuring the crack advance during the test, which is one of the main experimental challenges in EPFM procedures. Toughness values obtained from the EWF methodology have shown to be suitable to predict cracking related phenomena in AHSS sheets, such as edge cracking [1, 2] and crack propagation under crash loading [5]. Another method frequently used to characterize the fracture resistance of thin metal sheets is the Khan Tear Test (KTT). It has been extensively used to characterize the notch resistance of precipitation hardening aluminum alloys [8-10] and to evaluate toughness in different microstructures obtained by hot stamping of 22MnB5 steels [11] and in TWIP steels [12]. The main advantage of KTTs is that they are very simple tests and provide an estimation of the crack propagation resistance of the material.

The aim of this work is twofold; firstly, to determine the fracture resistance of several AHSS grades by means of these two methodologies, the EWF and the KTT; and secondly to assess the correlation between fracture toughness and local ductility in AHSS. The ability of the proposed methodologies to predict local ductility, as well as their main advantages and drawbacks, are discussed. Fracture toughness results are compared with different local formability and crash resistance parameters widely applied in the automotive sector:

- HER according to ISO 16630
- Bending angle from V-bending tests according to VDA 238-100
- Local strain at fracture from uniaxial tests obtained by means of Digital Image Correlation (DIC)
- Energy absorbed in axial impact tests

## 2. Fracture toughness measurements

### 2.1. Essential Work of Fracture

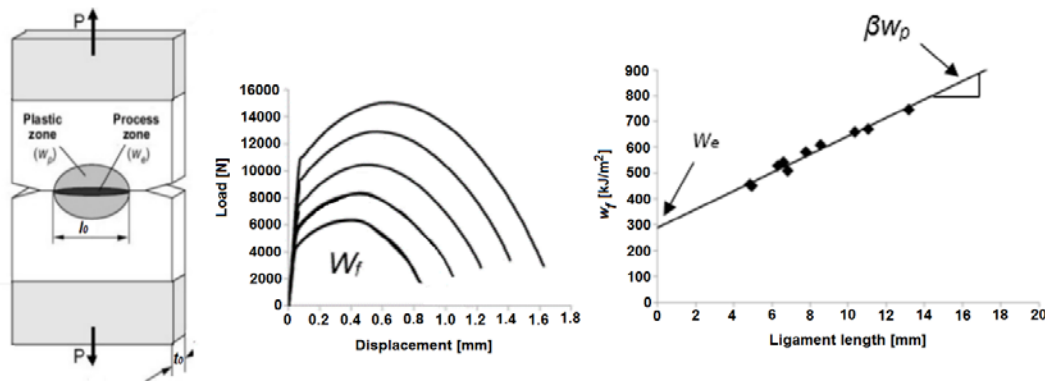
The Essential Work of Fracture (EWF) methodology was developed as an alternative method to quantify the ductile tearing resistance of thin ductile metal sheets [7]. The methodology permits to partition the total work of ductile fracture ( $W_f$ ) in two energetic contributions: an essential work of fracture ( $w_e$ ), spent in the fracture process zone and necessary to create new surfaces in the front of the crack tip and a non-essential plastic work ( $w_p$ ) surrounding the fracture area. The first term is proportional to the fracture surface and the second is proportional to the plastic volume, according to:

$$W_f = w_e l_0 t_0 + w_p \beta l_0^2 t_0 \quad (1)$$

where  $l_0$  is the ligament length (unfractured area ahead of the crack tip),  $t_0$  is the specimen thickness and  $\beta$  is a shape factor that depends on the shape of the plastic zone.  $W_f$  is obtained by testing a Double Edge Notched (DENT) specimen (Figure 1) at a constant displacement rate and integrating the area under the load vs displacement curve. The specific work of fracture ( $w_f$ ) is obtained by dividing  $W_f$  by the initial ligament area  $l_0 t_0$ . Thus, equation (1) can be rewritten as:

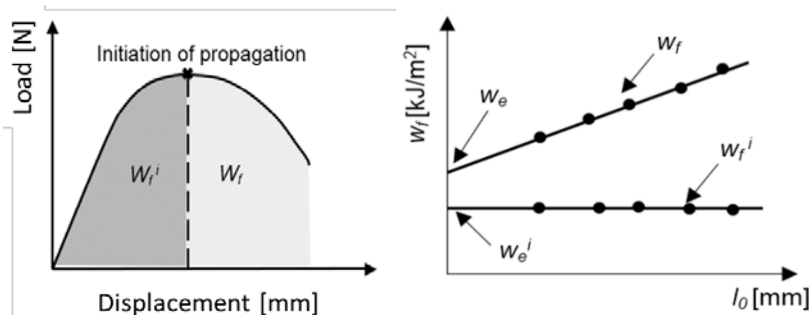
$$\frac{W_f}{l_0 t_0} = w_f = w_e + w_p \beta l_0 \quad (2)$$

If DENT specimens with different ligament lengths are tested and  $w_f$  is plotted against the ligament length  $l_0$ , a straight line with a positive intercept, which is the specific essential work of fracture ( $w_e$ ), is obtained (Figure 1).



**Figure 1.** DENT specimen and experimental determination of the EWF:  $W_f$  for different ligament lengths and plot of  $w_f$  against  $l_0$ , the intercept indicates the specific essential work of fracture,  $w_e$  [5].

The obtained toughness value,  $w_e$ , quantifies the energy dissipated within the fracture process zone during the ductile tearing process and it is a suitable parameter to describe the crack propagation resistance of thin ductile sheets [1, 2, 5, 7].  $w_e$  contains energetic contributions from both crack initiation and propagation since is an average value obtained from a linear regression of  $w_f$  values for the complete separation. However, as shown by Mai and Cotterell [13], the EWF methodology also permits to separate both contributions and determine a cracking initiation toughness value, the specific work for fracture initiation,  $w_e^i$ . The specific work for fracture initiation,  $w_f^i$  is calculated by integrating the area under load vs displacement curve until the onset of crack propagation (Figure 2, left). As observed in Figure 2 right,  $w_f^i$  is independent of the ligament length. Therefore,  $w_e^i$  is calculated from the average of  $w_f^i$  values.



**Figure 2.** Left: Determination of specific work of fracture at initiation of propagation ( $w_f^i$ ). Right: Variation of  $w_f^i$  in function of ligament length and determination of the specific essential work of fracture at cracking initiation,  $w_e^i$  [5].

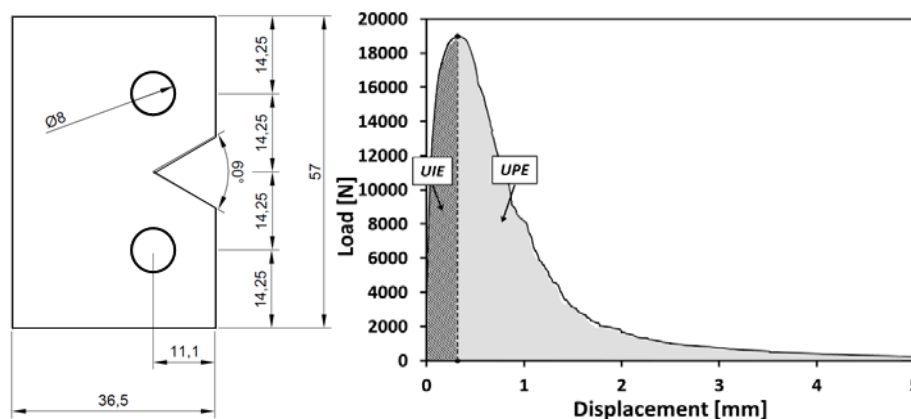
For the evaluation of the EWF, rectangular DENT specimens of 240 x 55 mm (machined at 90° respect to the rolling direction) with ligament lengths ranging from 6 to 16 mm were tested up to fracture at a constant speed of 1 mm/min. In order to obtain toughness values independent of the notch radius fatigue pre-cracks were nucleated on the notch root (notch radius,  $\rho \approx 0,1 \mu\text{m}$ ). More detailed information about the specimen geometry and test conditions is given in [5].

## 2.2. Khan Tear Tests

Khan Tear Tests (KTT) were originally developed to characterize the notch resistance of thin aluminum sheets [8]. The experimental procedure for KTT is described in ASTM B871 [14]. It consists in pulling at constant speed a single edge notched tensile (SENT) specimen with no prior fatigue pre-crack but a sharp notch. In this case, the notch radius was of 150  $\mu\text{m}$ , obtained by electrical discharge machining (EDM). The specimens were machined at transverse direction and KTTs were conducted at a constant displacement rate of 1 mm/min. An initial gauge length of 10 mm was used for load-line displacement

measurement. The specimen geometry and the characteristic load vs displacement curve are shown in Figure 3.

The notch resistance is characterized by the unit initiation energy (UIE) and the unit propagation energy (UPE). UIE represents the notch resistance to nucleate a crack and is calculated from the area under the load-displacement curve at maximum load. UPE is the primary result of the tear test and it is calculated from the area after the maximum load. It provides a measure of the combination of strength and ductility that permits a material to resist crack growth and it has significance as a relative index of fracture toughness. As indicated in the standard ASTM B871 [14], the method does not provide an absolute measure of the material resistance against crack propagation but a comparative measure of resistance to unstable fracture in the presence of crack-like stress concentrators.



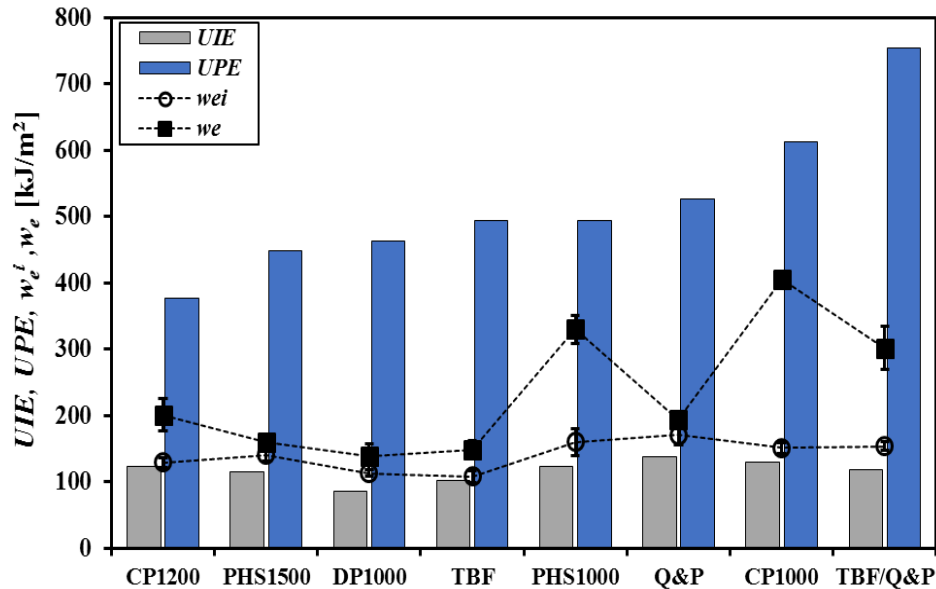
**Figure 3.** SENT specimen for tear tests (left). Load–displacement curve for a Kahn Tear Test (right). The UIE is calculated from the area under the curve before maximum load, and the UPE after maximum load.

### 2.3. Comparison between EWF and KTT

Figure 4 compares fracture toughness results obtained by means of the EWF methodology and KTT. On the one hand, it is interesting to note that, even though the difference in notch radius between the two test configurations, there is a good correspondence between the values of crack initiation resistance,  $w_e^i$  and UIE. It means that for the SENT specimen the machined sharp notch ( $\rho = 150 \mu\text{m}$ ) closely represents the stress singularity of a crack. It supposes an advantage respect to the EWF tests since, it avoids the propagation of fatigue pre-cracks in the notch root, which is the most time consuming part in fracture mechanical characterizations.

However, whereas results for crack initiation resistance are very similar, large differences are observed in the values associated to the crack propagation resistance,  $w_e$  and UPE. For example, DP1000 and TBF show UPE values (464 and 493  $\text{kJ/m}^2$  respectively) comparable to PHS1000 (494  $\text{kJ/m}^2$ ), which contrasts with the large differences observed in  $w_e$ : DP1000 and TBF shows the lowest  $w_e$  ( $138 \pm 20$  and  $149 \pm 13 \text{ kJ/m}^2$ ), whereas PHS1000 exhibits a much greater  $w_e$  value ( $330 \pm 21 \text{ kJ/m}^2$ ). It is also observed that, according to UPE values, TBF/Q&P presents the greatest crack propagation resistance (755  $\text{kJ/m}^2$ ). On the contrary, CP1000 shows the higher  $w_e$  ( $405 \pm 11 \text{ kJ/m}^2$ ). These differences can be associated to both the effect of the specimen geometry during crack propagation in KTT and to the conceptual dissimilarities between the two methodologies. It must be noted that after crack initiation, the load rapidly evolves from uniaxial tensile to bending and, therefore, crack propagates under a complex mixed loading mode. It give rise to UPE values that cannot be directly compared with pure Mode I fracture resistance, as given by  $w_e$ . Moreover, the energy calculated in the UPE is not only an energy for new fracture surface creation but it also contains the energetic contribution of the dissipated plastic work, which depends on the specimen geometry. In this regard, the EWF methodology separates both contributions and the toughness value  $w_e$  only quantifies the work spent in the fracture process zone to create new surfaces at the crack tip. Therefore,  $w_e$  better represents the steady state crack propagation resistance and it can be considered a material property, equivalent to the elastic plastic fracture

mechanics toughness value  $J_C$  [13]. On the contrary, as mentioned before, UPE can be only used as a comparative value for crack propagation resistance for a given material. It is not a material property and it should be only used to rank materials crack propagation resistance. However, as observed in Figure 4, UPE can significantly overestimate such property.



**Figure 4.** Results of EWF and KTT for different AHSS grades. EWF results taken from reference [5].

### 3. Local formability and crash behaviour

#### 3.1. Stretch flangeability

The results of Hole Expansion Tests (HET) according to ISO 16630 for the investigated AHSS grades are summarized in Table 1. Initial punched holes of 10 mm in diameter were used for the expansion tests (punch to die clearance of  $12 \pm 2$  %). Hole Expansion Ratio (HER) values are taken from reference [1].

#### 3.2. Bendability

3-point V-bending tests according to VDA 238-100 were performed at voestalpine Stahl following the procedure described in the work of Suppan et al. [15]. Specimens were bent with a sharp punch ( $r=0.4$  mm) at a speed of 20 mm/min with the bending line lying parallel to rolling direction (bending strain in transverse direction). Free rotating rollers with a radius  $R=15$  mm were used as shoulders and were separated according to:

$$d = 2t + 0.5 \quad (3)$$

where  $d$  is the free space between the rolls and  $t$  is the specimen thickness. All values are in mm.

The punch force and displacement was recorded and the test was stopped when the maximum punch stroke at around  $160^\circ$  bending angle was reached. Bending angle was indirectly calculated from the punch displacement as indicated in [16]. In the present work, the bendability was characterized by means of the critical angle ( $\alpha_{\text{crit}}$ ), defined as the angle at which the first visible crack was detected. In most cases, the critical angle coincided with the bending angle at maximum force ( $\alpha_{\text{crit}} = \alpha_{\text{Fmax}}$ ), except for CP1000, where first visible cracks were detected up to  $30^\circ$  after the maximum load. Values of  $\alpha_{\text{crit}}$  are reported in Table 1.

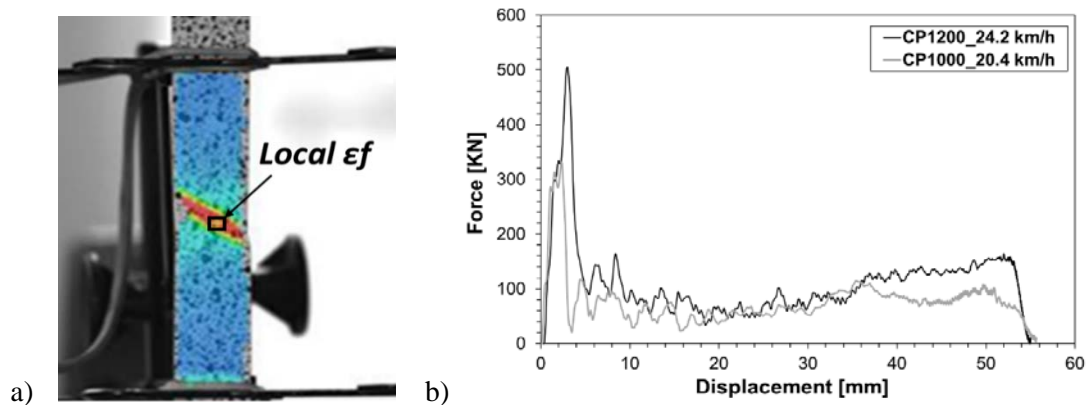
#### 3.3. Local strain at fracture from uniaxial tensile tests assisted by digital image correlation

Uniaxial tensile tests according to EN-ISO 6892 were performed in transverse direction. A Digital Image Correlation (DIC) equipment was used to monitor and determine the strain during the whole test. The

DIC equipment permits to measure local strains within the necking area. The local strain level after necking is much greater than the obtained by conventional extensometry with much larger 80 mm gage length and it better defines the local ductility potential of the material. Images were recorded at a frame rate of 10 images/second. A facet size and a step size of 11 and 9 pixels respectively were used. The local strain at fracture ( $Local \epsilon_f$ ) was determined from the point of maximum deformation (major logarithmic strain) at the stage before fracture (Figure 5a).  $Local \epsilon_f$  values are summarized in Table 1.

### 3.4. Maximum energy absorbed in axial impact tests

Crash resistance of AHSS is usually evaluated according to the energy absorbed, deformation, cracking and global appearance of the specimens after crash testing. In this work, the maximum energy absorbed in axial crash tests was used to characterize the impact resistance of the investigated steel grades. The energy absorbed during crash loading was calculated by integrating the area under the force vs impactor displacement (Figure 5b). To avoid the influence of the specimen thickness, the energy values from [5] were normalized by the cross-section area of the crashed sample. The values of impact energy absorbed per unit area are shown in Table 1. Details about crash specimen geometry and the experimental procedure followed for crash characterization can be found in reference [5].



**Figure 5. a)** Determination of local strain at fracture ( $Local \epsilon_f$ ) from uniaxial tensile tests with DIC. **b)** Force vs impactor displacement curves obtained from axial impact tests [5].

**Table 1.** Local formability measurements and crash behaviour for the investigated AHSS grades. Standard deviation is indicated when available. HER values and energy absorbed in axial impact tests are extracted from references [1] and [5] respectively. Mechanical properties for the transverse direction and sheet thickness are also given.

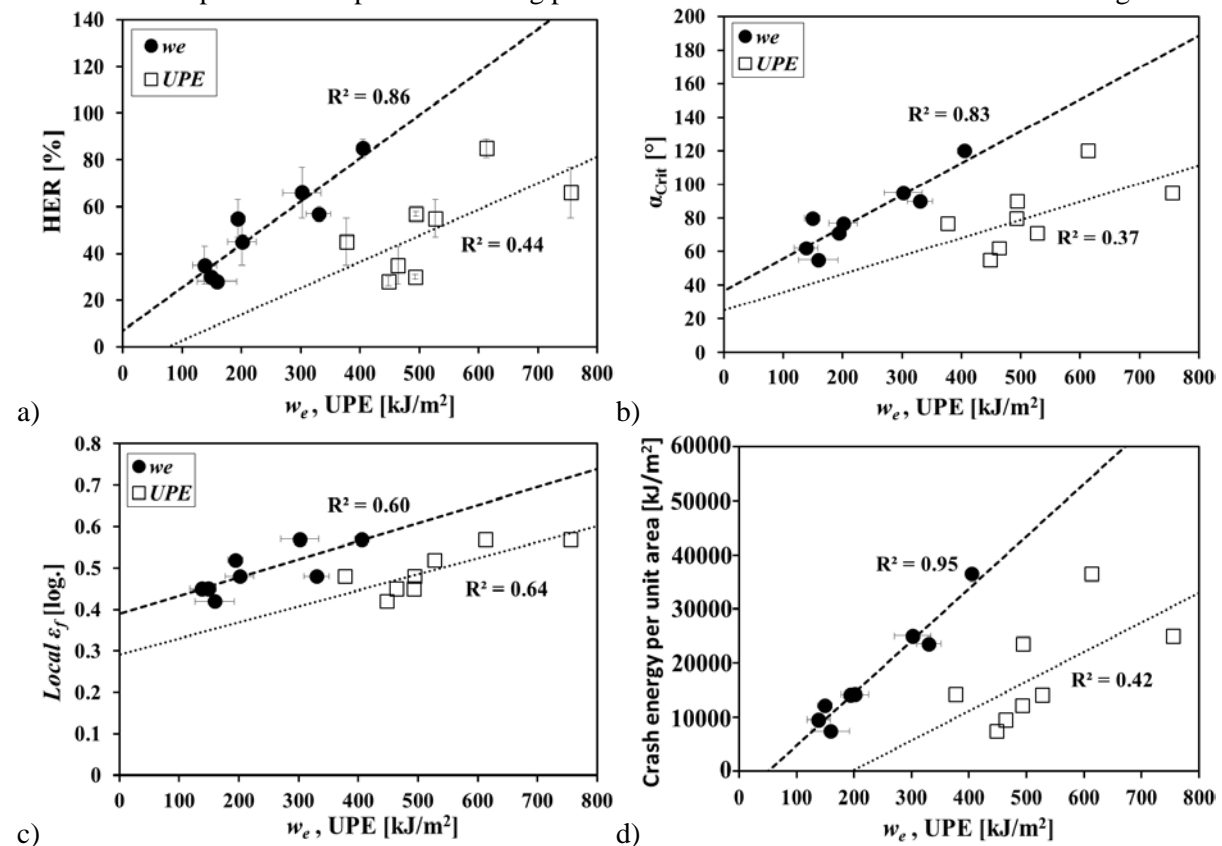
	Thickness, t [mm]	HER [%]	$\alpha_{crit}$ [°]	$Local \epsilon_f$ [log.]	Axial impact energy per unit area [kJ/m <sup>2</sup> ]	Yield stress, $\sigma_{ys}$ [MPa]	Ultimate tensile strength, $\sigma_{UTS}$ [MPa]	Elongation at fracture, A <sub>80</sub> [%]
<b>CP1200</b>	1.6	45 ± 10	77	0.48	14229	1041	1218	6.0
<b>PHS1500</b>	1.5	28 ± 2	55	0.42	7461	1075	1552	5.2
<b>DP1000</b>	1.4	35 ± 8	62	0.45	9592	738	1027	10.3
<b>TBF</b>	1.5	30 ± 1	80	0.45	12186	725	1019	14.7
<b>PHS1000</b>	1.5	57 ± 1	90	0.48	23626	988	1007	7.3
<b>Q&amp;P</b>	1.4	55 ± 8	71	0.52	14122	909	1209	7.4
<b>CP1000</b>	1.4	85 ± 4	120	0.57	36504	908	1002	8.1
<b>TBF/Q&amp;P</b>	1.4	66 ± 11	95	0.57	25047	876	1026	11.3

## 4. Fracture toughness vs local ductility

Figure 6 plots fracture resistance results ( $w_e$  and UPE) against local formability and crash resistance parameters. It is observed that  $w_e$  shows a good correlation with all the different local ductility measurements, especially with ISO 16630 HER and maximum energy absorbed in axial impact tests



( $R^2=0.86$  and  $0.95$  respectively), as previously reported and discussed by Casellas et al. [1] and Frómeta et al. [5]. It is also found a quite good correlation with the critical bending angle,  $\alpha_{crit}$  ( $R^2=0.83$ ) and the local strain at fracture from uniaxial tensile tests ( $R^2=0.60$ ). Such results confirm the straight relationship between fracture toughness and the local ductility of AHSS and pose the essential work of fracture as a suitable material property to predict local formability and crash resistance. On the other hand, crack propagation resistance results from KTT (UPE), overall, show a low prediction ability for local formability and crash performance assessment. UPE shows a poor correlation with HER ( $R^2=0.44$ ), bending angle ( $R^2=0.37$ ) and impact energy per unit area ( $R^2=0.42$ ). Such correlation is improved for local strain at fracture ( $R^2=0.64$ ), which is comparable to the observed with  $w_e$ . Therefore, it is shown that, even though the UPE can give an estimation of the crack propagation resistance of the material, it is not a reliable parameter to predict cracking phenomena related to the material's fracture toughness.



**Figure 6.** Fracture toughness results ( $w_e$  and UPE) against different local ductility parameters: **a)** HER according to ISO 16630 [1]. **b)** Critical bending angle ( $\alpha_{crit}$ ) from V-bending tests. **c)** local strain at fracture ( $Local \ \epsilon_f$ ) from uniaxial tensile tests with DIC. **d)** Maximum energy absorbed in axial impact tests per unit area.

## 5. Summary and conclusions

The experimental investigations carried out in this work allow pointing out fracture toughness, in terms of essential work of fracture, as a suitable material property to estimate the local ductility of AHSS sheets. This conclusion is based on the good correlation observed between  $w_e$  and the different local ductility parameters for a wide range of AHSS grades.

This work compared the ability of fracture resistance values from the EWF methodology and KTT to understand crack-related problems in AHSS, as local formability or crashworthiness. Even though crack initiation values from KTT are quite reliable and very similar to the obtained by means of the EWF methodology, the crack propagation resistance in such tests is strongly influenced by the changing load mode during the test. UPE values show a poor correlation with the evaluated local ductility and



crash resistance parameters. The good prediction capability of  $w_e$  compared with UPE can be understood considering their intrinsic differences, i.e.  $w_e$  accounts for the dissipated energy to create new surfaces in Mode I during crack propagation whereas UPE contains the contribution from plastic work during crack propagation in a mixed loading mode. Local ductility and crashworthiness are more related to crack propagation than to first crack nucleation, which explains their good correspondence with essential work of fracture values,  $w_e$ .

### Acknowledgments

The authors would like to thank Dr. Clemens Suppan, Dr. Johannes Rehr and Dr. Patrick Larour from voestalpine Stahl GmbH for providing the results of V-bending tests and for the support in the analysis of results and useful discussions.

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